RADIOGRAPHIC RESULTS FOR THE ROD-PINCH DIODE SCALED UP TO 6 MV *

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Abstract

The rod-pinch diode is evaluated as a pulsed radiographic source for diode voltages up to 6 MV on the ASTERIX generator. Peak currents of 105 to 135 kA are delivered to the diode for peak voltages of 5.2 to 6.3 MV. The diode couples efficiently to the generator for 1.6-, 2.0-, and 3.0-mm diameter tungsten (or gold) anode rods producing a 40-ns radiation pulse. The coupling is degraded if the anode-cathode gap ($R_C - R_A$) is too small (7.5 mm), if the anode rod extension is too short (10 mm), or if the aspect ratio R_C/R_A is too large (20). For the standard anodes considered here, the figure-of-merit (FOM) is largest [11 rad(air)/mm^2] for a 1.6-mm diameter anode, corresponding to an on-axis (0°) dose of 28 rad(air) at 1 meter from the source and a 1.55-mm source diameter (LANL measure). For a 2-mm diameter anode, the largest FOM [9.2 rad(air)/mm^2] is obtained for a 1.95-mm source diameter and a 35-rad(air) dose. Blunt-end anodes have larger on-axis source diameters and smaller FOMs than tapered-tip anodes. Measured angular distributions indicate that the dose increases monotonically from 0° to 80° by a factor of 1.6 to 1.8 and suggest that the electron distribution incident on the anode rod peaks at a large angle from the forward direction.

I. INTRODUCTION AND SETUP

The rod-pinch diode provides an intense, pulsed, small-diameter, megavolt, bremsstrahlung source for point-projection radiography.[1] Previously, this diode was operated successfully up to 4 MV on the ASTERIX generator in France, producing doses at 1 meter from the source of 16 and 20 rad(Si) for source diameters (LANL measure) of 1.6 and 2.2 mm, respectively.[2] The success of these experiments led to an effort to extend the evaluation of this source to voltages exceeding 6 MV. ASTERIX was modified to operate in positive polarity at higher voltage[3] in order to test the performance of this diode up to 6 MV and to identify limitations in operating the diode in this polarity. In addition, the radiation diagnostics were expanded to provide detailed angular distributions of the radiation emitted from 0° to 90° and to measure the source size both on-axis and at 90°.

The arrangement of the diode is shown in Fig. 1. A 6.4-mm diameter carbon rod connects the anode stalk (center conductor) of the generator to a smaller diameter tungsten (or gold) rod which extends 16 mm beyond the cathode with the last 10 mm tapered to a point. The cathode is located 20 cm from the anode stalk, and the carbon/tungsten junction is about 5 cm from the cathode. Electrons emitted from the cathode pinch onto the tip of the anode rod and produce an intense small-diameter radiation source. Anode rods of 1.0, 1.6, 2.0, and 3.0 mm diameter are used, and the ratio of the cathode-to-anode radius R_C/R_A ranges from 11 to 16. In this paper results are given for the standard anode geometry shown in Fig. 1 in contrast with the composite anode geometry discussed in Refs. 4-6. For peak voltages of 5.2 to 6.3 MV, peak currents delivered to the diode range from 105 to 135 kA. A description of the electrical measurements used to determine the current and voltage at the load is given in Ref. 3. The 3.2-mm thick carbon (or aluminum coated with carbon) cathode usually survives, while the tungsten

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14. ABSTRACT
The rod-pinch diode is evaluated as a pulsed radio-graphic source for diode voltages up to 6 MV on the ASTERIX generator. Peak currents of 105 to 135 kA are delivered to the diode for peak voltages of 5.2 to 6.3 MV. The diode couples efficiently to the generator for 1.6-, 2.0-, and 3.0-mm diameter tungsten (or gold) anode rods producing a 40-ns radiation pulse. The coupling is degraded if the anode-cathode gap (RC RA) is too small (7.5 mm), if the anode rod extension is too short (10 mm), or if the aspect ratio RC/RA is too large (20). For the standard anodes considered here, the figure-of-merit (FOM) is largest [11 rad(air)/mm2] for a 1.6-mm diameter anode, corresponding to an on-axis (0°) dose of 28 rad(air) at 1 meter from the source and a 1.55-mm source diameter (LANL measure). For a 2-mm diameter anode, the largest FOM [9.2 rad(air)/mm2] is obtained for a 1.95-mm source diameter and a 35-rad(air) dose. Blunt-end anodes have larger on-axis source diameters and smaller FOMs than tapered-tip anodes. Measured angular distributions indicate that the dose increases monotonically from 0° to 80° by a factor of 1.6 to 1.8 and suggest that the electron distribution incident on the anode rod peaks at a large angle from the forward direction.

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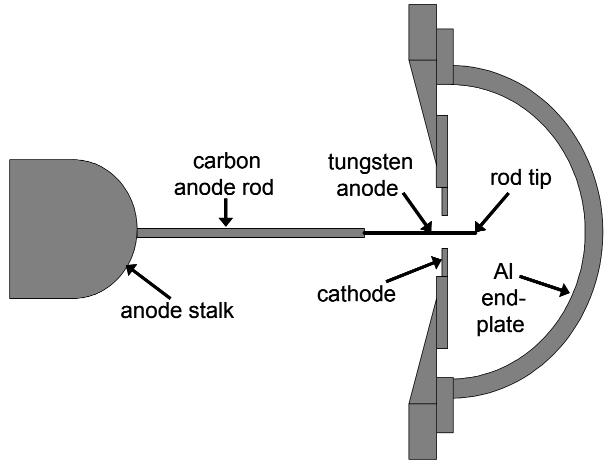

Figure 1. Setup of the rod-pinch diode on ASTERIX for angular-distribution measurements.

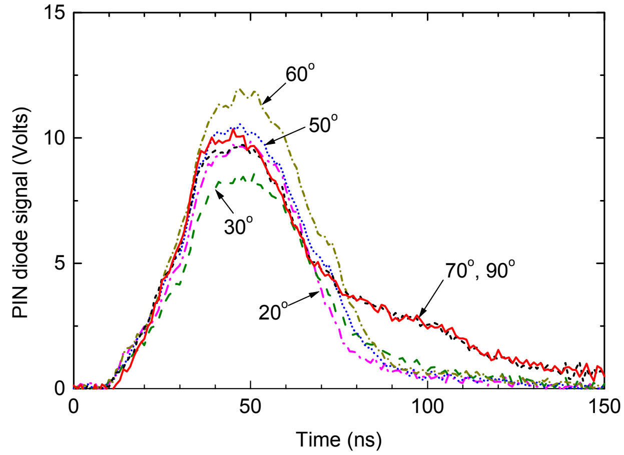

Figure 2. Signals measured by the *pin* diode detectors for a 1.6-mm diameter tapered Au anode.

rod is destroyed. The anodized aluminum hemispherical end-plate (1-cm thick) provides uniform attenuation of the radiation emitted at angles ranging from −90° to +90° and simplifies interpretation of the angular-distribution measurements.

II. RADIATION DIAGNOSTICS

A pinhole camera, located at −45° off-axis, is used to image x-ray emission from the anode onto film. These images indicate that electrons pinch onto the tip of the anode rod producing a few-mm-long intense x-ray source at the end of the rod. More detailed measurements of the source size are determined from analysis of photographic images of an 82-cm radius tungsten rolled-edge located 40 cm from the rod tip. Images are recorded with source magnifications of 4 and 5 both on-axis and at −80° off-axis. Results from this imaging are described in Ref. 6.

Angular distributions are measured with thermoluminescent dosimeters (TLDs) and with Si *pin* diode detectors. Doses are measured with an array of five TLDs located 2 meters from the rod tip at angles of 2°, 20°, 40°, 60° and 80°. Inverse square scaling is used to determine the dose at 1 meter. Each TLD consists of three 3-mm × 3-mm × 0.9-mm thick LiF chips housed in a 2.0-cm diameter × 2.2-cm long plastic (delrin) cylinder for equilibration. Time histories of the radiation are measured with an array of six lead-collimated Si *pin* diode detectors located at −20°, 30°, 50°, −60°, 70° and 90°. The *pin* diodes (3-mm^2 area × 0.25-mm thick) are mounted within a 6-mm diameter hole in a 6.0-cm diameter × 6.0-cm long lead collimator. In addition, 6.0-mm-thick lead filters are used to attenuate the signals in order to avoid saturation. These detectors are located either 2 or 3 meters from the anode rod tip. Typical results for a shot with a 1.6-mm diameter tapered gold rod are shown in Fig. 2. The pulse shapes are similar at all angles except at 70° and 90° where a long tail is present. This tail increases for larger dose and is not present for smaller dose. The tail is attributed to delayed charge collection in the *pin* diode for large doses. If the tail is ignored, then the *pin* diode signals at different angles have similar pulse shapes for all the shots in this experiment, and the FWHM of the pulse is 40 ± 5 ns.

III. RESULTS

Two constraints on the rod-pinch-diode geometry were identified in the previous experiment on ASTERIX.[2] First, the impedance behavior is sensitive to the aspect ratio R_C/R_A. If R_C/R_A exceeds 16, the impedance decays rapidly. Second, an anode-cathode (A-K) gap ($R_C - R_A$) larger than 6.5 mm was required at 4 MV to avoid excessive gap closure during the pulse. In the present experiment at higher voltage, a 1-mm diameter anode shot with $R_C - R_A$ = 7.5 mm and R_C/R_A = 16 exhibits rapid impedance decay and small dose. In contrast, similar shots with 1.6-mm diameter rods and $R_C - R_A$ = 8.2 mm exhibit less rapid impedance decay and larger dose. A bipolar pre-pulse was identified as a contributor to gap closure and impedance decay in the previous experiment at 4 MV.[2] In the present experiment, the pre-pulse is of similar shape, but larger in magnitude. Peak values are +16 kV and −8 kV compared with +14 kV and −7 kV at 4 MV. This increase is consistent with the larger A-K gap required in the present experiment to avoid gap closure.

Several variations of the rod-pinch are made in this experimental study to optimize the diode as a radiography source. The figure-of-merit (FOM) is used to compare the performance for different diode configurations. The FOM is given by the on-axis dose divided by the square of the source diameter. The source diameter, defined by the LANL measure, is used for this study. The LANL measure (SD_{LANL}) is determined from the 50% point on the modulation transfer function, i.e., the Fourier transform of the line-spread function (LSF).[2] Typical LSFs for two shots with 1.6-mm diameter anode rods are presented in Fig. 3. The LSFs for these tungsten and gold rods are nearly identical, and SD_{LANL} = 1.7 mm, only 0.1

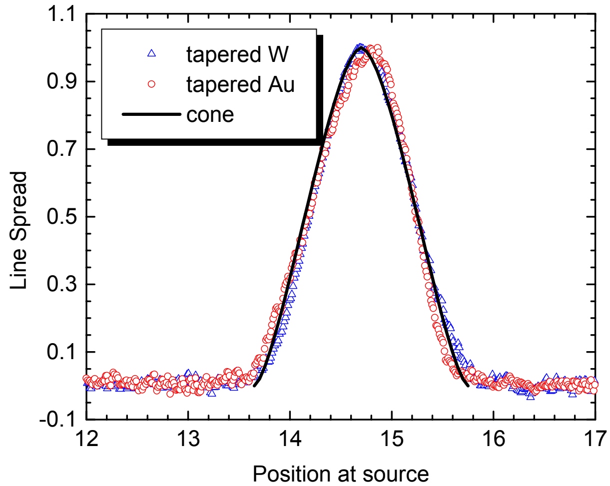

Figure 3. Measured LSFs for 1.6-mm diameter W and Au anode rods. The LSFs are fit to a uniformly radiating cone of 2.1-mm base-diameter (solid line).

mm larger than the rod diameter. The shape of the LSF fits uniform radiation from the volume of a 2.1-mm base-diameter conical source (solid line in Fig. 3). This shape is expected for uniform deposition of high-voltage electrons in the tapered anode tip. However, the base-diameter of the cone is 0.5 mm larger than the 1.6-mm rod diameter. The LSFs in this experiment are devoid of wings on the distribution that were present in the ASTERIX experiment at 4 MV.[2]

The 16-mm anode-rod extension was varied from 10 mm to 22 mm and to 30 mm on three shots. For a 10-mm extension of a 2-mm diameter rod, the impedance collapses rapidly, the voltage is reduced, and the FOM is 8.5 rad(air)/mm^2 compared with 11 rad(air)/mm^2 for a 16-mm extension. This behavior is presumably due to plasma expanding from the anode tip and contributing to A-K gap closure during the pulse. For a 22-mm extension of a 1.6-mm diameter rod, the FOM is 9.6 rad(air)/mm^2 but decreases to 6.7 rad(air)/mm^2 for a 30-mm extension. This decrease is due to a smaller electron current and dose presumably because the ion current increases for a longer rod at the expense of the electron current. A 16-mm extension was used for most of the shots in this experiment. However, a few-mm-longer extension could be used to move the anode plasma farther away from the A-K gap without degrading the FOM significantly.

Angular distributions measured with the TLDs are presented in Fig. 4 for the different diameter anode rods. The dose increases monotonically with angle for all four rods. The 80°/0° ratio is a factor of 1.6 to 1.8 for the 1.6, 2.0, and 3.0-mm diameter rods and a factor of 2.5 for the 1-mm diameter rod. The dose increases at all angles as the rod diameter is increased from 1.0 to 2.0 mm. However, the 3-mm dose is essentially the same as the 2-mm dose at all angles. Ratios (90°/20°) inferred from integrated PIN diode signals in the present experiment are consistent with these TLD ratios. However, the ratios are not consistent with the large anisotropy (80°/10° ≈ 4) measured in the previous ASTERIX experiment,[4] and

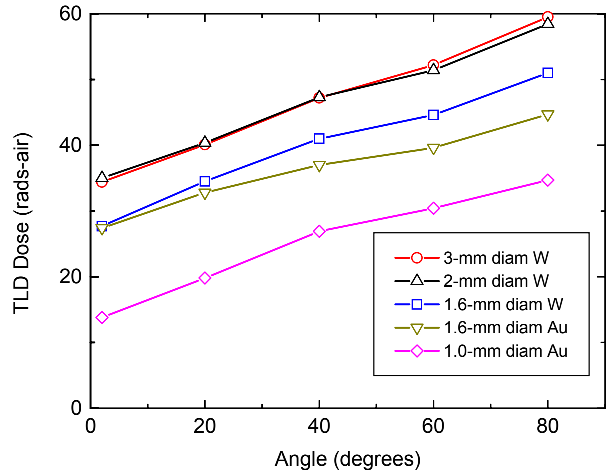

Figure 4. TLD angular-distribution measurements for different diameter tapered anodes.

the large anisotropy results are probably incorrect.

A few shots were taken with a blunt end on the anode rod rather than the taper to a point. Angular distributions measured for 1.6-mm diameter blunt and tapered tungsten or gold rods are compared in Fig. 5. The blunt-rod distributions increase monotonically with angle with an 80°/0° ratio of 1.7, similar to the tapered-rod distributions. However, the blunt rods tend to produce a little more dose, particularly off-axis.

There appears to be little difference between a tungsten or gold anode as a radiographic source. The LSFs are similar (see Fig. 3), the on-axis doses are the same (see Fig. 4), and the angular distributions are similar for tapered rods (see Fig 5). The only difference appears to be a somewhat larger off-axis dose for a blunt tungsten rod.

The on-axis diameter of the source is measured with the rolled-edge technique on every shot. Values of SD_{LANL}, extracted from the measured LSFs, are presented in Fig. 6 for the different diameter anodes. For a tapered anode, SD_{LANL} increases from 1.3 mm for a 1-mm diameter rod

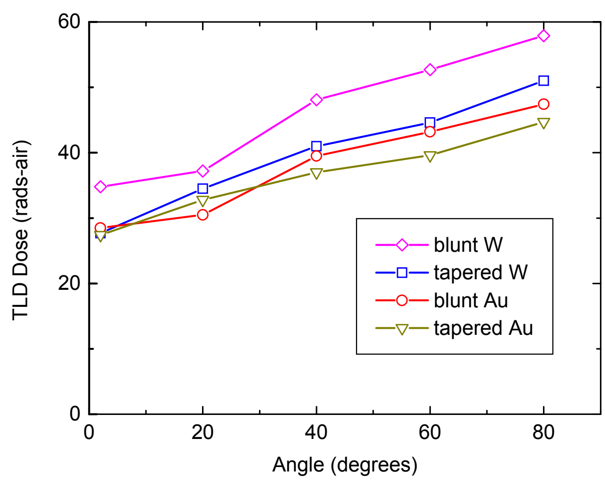

Figure 5. TLD angular distributions for 1.6-mm diameter anodes with either a tapered tip or a blunt end.

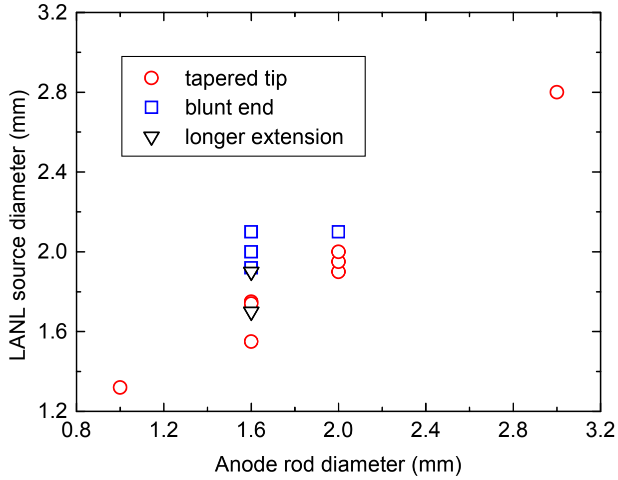

Figure 6. On-axis source diameters measured for different diameter anodes.

to 2.8 mm for a 3-mm diameter rod; an increase with rod diameter that is less than one-to-one. For a 1.6-mm diameter rod, SD_{LANL} = 1.7 ± 0.1 mm (3-shot average), and for a 2.0-mm diameter rod, SD_{LANL} = 1.90 ± 0.05 mm (3-shot average). Blunt-end anodes have significantly larger source diameters: 2.0 mm for a 1.6-mm diameter rod and 2.1 mm for a 2.0-mm diameter rod. SD_{LANL} is not altered significantly for a tapered anode with a 22-mm extension, but is increased by about 12% for a 30-mm extension.

The FOM is presented in Fig. 7 for the different diameter anodes. The largest FOM is 11 rad(air)/mm^2 for a 1.6-mm diameter rod. The largest FOM for a 2.0-mm diameter rod is 9.2 rad(air)/mm^2 The larger dose for the 2.0-mm diameter rod compensates for the larger SD_{LANL} for this rod to maintain a large FOM. The FOM is smaller for a 3.0-mm diameter rod because SD_{LANL} is so large. The FOM is smaller for blunt-end rods than for tapered rods because SD_{LANL} is larger. The FOM is still large [9.6 rad(air)/mm^2] for a 22-mm anode extension, but is smaller [6.7 rad(air)/mm^2] for a 30-mm extension.

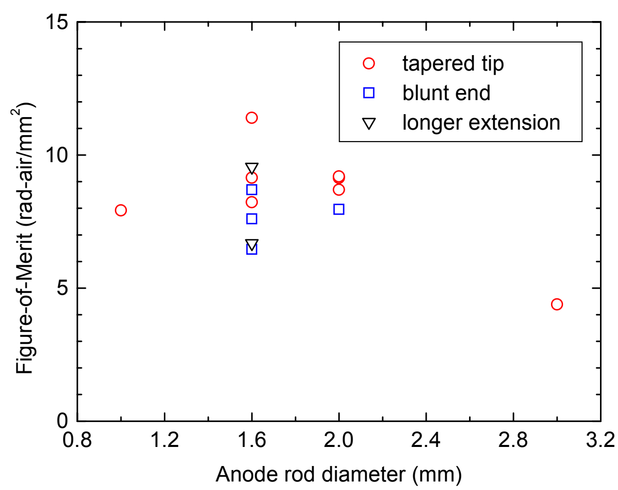

Figure 7. FOM measured for 1.0- to 3.0-mm diameter anode rods

IV. CONCLUSIONS

The rod-pinch diode operates without excessive impedance collapse at peak voltages up to 6 MV for anode-rod diameters of 1.6 to 3.0 mm and for aspect ratios of 11 to 16. Radiation on-axis is emitted in a 40-ns FWHM pulse from a source comparable in size to the anode-rod diameter. For a 1.6-mm diameter rod, the on-axis dose at 1 meter is 27 rad(air) corresponding to a FOM of 11 rad(air)/mm^2. For a 2-mm diameter rod, the on-axis dose at 1 meter is 35 rad(air) corresponding to a FOM of 9.2 rad(air)/mm^2. Anodes tapered to a point have a larger FOM than blunt-end anodes. Anode-rod extensions beyond the cathode of 16 or 22 mm give good results. If the extension is 30 mm, the dose and FOM are degraded. If the extension is only 10 mm, the diode impedance collapses prematurely, and the voltage and dose are reduced.

The rod-pinch anode can be modified to maintain good impedance behavior in the A-K gap by extending a low-Z anode rod (2-mm diameter) through the cathode and inserting a short (10-mm long) high-Z converter (1-mm diameter) onto the end of the rod to provide a small on-axis source. Such composite anodes were tested on ASTERIX in this experiment, and their performance is described in a companion paper.[6] The FOM is as large as 13.6 rad(air)/mm^2 for a composite anode.

Angular distributions indicate that the dose increases monotonically from 0° to 90°. These results suggest that the electron distribution incident on the rod tip is not peaked in the forward direction, but at a large angle to the forward direction. Calculated angular distributions are compared with these measurements in Ref. 7. To take advantage of the large dose off-axis and to extend the source to higher voltage, operating the rod-pinch diode in negative polarity is being considered.[7,8]

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